10950 Session 2022
A3 - Transmission & Distribution Equipment
PS 2 / Decarbonisation of T&D Equipment

Transmitted Overvoltage Requirements for Instrument Transformers

Tin PERKOVIĆ
Končar – Instrument Transformers, Inc.
Croatia
tin.perkovic@koncar-mjt.hr

Igor ŽIGER
Končar – Instrument Transformers, Inc.
Croatia
igor.ziger@koncar-mjt.hr

Miroslav BONIĆ
Končar –Electrical Engineering Institute
Croatia
mbonic@koncar-institut.hr

Danijel BREZAK
Končar –Electrical Engineering Institute
Croatia
dbrezak@koncar-institut.hr

SUMMARY

Instrument transformers are subjected to overvoltages caused by lightning, network switching phenomena and selected failure stages. Since the secondary circuits of instrument transformers supply sensitive equipment, instrument transformers themselves should be designed to limit the transferred overvoltage and thus protect the secondary equipment and ensure its disturbance-free operation.

Instrument transformer standards have different requirements on the issue of transmitted overvoltage. The most elaborate procedure is currently present in the IEC 61869-1 standard. However, since that standard is under revision, the current draft (i.e. 38/652/CD) introduced substantial changes in the procedure of transmitted overvoltage testing. In addition, transmitted overvoltage requirements are being introduced in the joint IEC/IEEE 63253-5713-8 standard for Station Service Voltage Transformers (i.e. 38/633/CD) which also sparked a discussion on the applicability of the existing and novel test procedures and requirements to this type of equipment.

It is the specific aim of this paper to address the aforementioned issues, provide and document the experiences with testing of transmitted overvoltages on different instrument transformer types. Current Transformers, Voltage Transformers and Station Service Voltage Transformers are considered within the scope of the paper. Furthermore, the obtained results are contrasted to the results of grounding shield test, a simple routine test for high-voltage instrument transformers, which has been long present in the IEEE C57.13 and CAN/CSA 61869 standard families.

KEYWORDS
Instrument transformers, Station Service Voltage Transformers, Transmitted overvoltages, High-voltage testing

1. INTRODUCTION

High voltage faults, lightning and switching operations in air-insulated substations can cause high levels of high frequency overvoltages (from few hundred kHz to a few MHz) [1]. This is especially true for disconnector operations, since they inevitably cause multiple high frequency strikes and re-strikes until the free-burning arc is extinguished between their contacts [2][3]. The incepted strikes and restrikes are seen as electromagnetic transients with a very fast rate of rise which can be transferred to other high voltage equipment located in the vicinity of the operating disconnector [4], [5], [6].

One of the main transport systems for such transients to the low voltage circuits are instrument transformers [7]. Due to the nature of typical instruments connected to their secondary side (meters, protection relays, auxiliary devices, and electronics), which can be sensitive to transmitted overvoltages, protection against and control of transmitted overvoltages is a significant concern to various grid operators [8].

To test and verify ensure sufficient protection for equipment connected to the secondary terminals of instrument transformers, different applicable clauses have been implemented into various international standards. One of the primary objectives of this paper is to gather different approaches included in different international standards and compare them on relevant high-voltage instrument transformers of different types. The comparison will mostly be based on actual testing performed on these units according to different standard requirements with varying parameters. The aim is to provide context, history, and author recommendations on the topic.

In addition, a dedicated section focuses on Station Service Voltage Transformers (also known as Power Voltage Transformers), which are still a novel occurrence in power systems worldwide and have a vastly more diversified load than conventional instrument transformers [9]. For that reason, it is debateable to which extent the requirements for instrument transformers are applicable to those types of units.

The overall idea of this paper is to serve as a guide for specifying, testing, and evaluating performance of instrument transformers regarding overvoltages transmitted to their secondary circuits. It should be noted that all considerations and conclusions of this paper were obtained and intended for equipment used in Air Insulated Substations (AIS) and no equipment intended for use in Gas Insulated Substations was considered.

2. COMPARISON OF REQUIREMENTS FOR TRANSMITTED OVERVOLTAGES PRESENT IN DIFFERENT INTERNATIONAL STANDARDS

Currently, international instrument transformers predominantly use two different approaches to evaluate transmitted overvoltages.

The currently valid IEC 61869-1:2007 standard defines a special test procedure which evaluates transmitted overvoltage by applying a low voltage signal to the primary winding of instrument transformers [10]. On the other hand, the IEEE C57.13 standard family specifies a routine grounding shield check which does not specifically test the level of transmitted overvoltages, rather the existence of a dedicated grounded shield between the windings which is considered as a sufficient way for reducing the capacitive coupling between primary and secondary windings and consequently the amplitude of transmitted overvoltage [11], [12]. Canadian standard group CAN/CSA C61869-1:14 is essentially a compilation of both standards, using an IEC base with relevant IEEE clauses added to that base. For that reason, it contains both requirements mentioned above, which is a good approach [13].

IEC 61869-1:2007 standard is, at the time of writing this paper, in final stages of a major revision, with the current draft (i.e. 38/652/CD) introducing substantial changes in the procedure of transmitted overvoltage testing by introducing a test procedure that requires the application of fast-front high-voltage waveform. These changes caused a tangible amount of controversy within the working group with many comments addressing this specific issue [14].

Lastly, transmitted overvoltage requirements are being introduced in the joint IEC/IEEE 63253-5713-8 standard for Station Service Voltage Transformers (i.e. 38/633/CD) which also sparked a discussion on the applicability of the existing and novel test procedures and requirements to this type of equipment [15].

Based on the available requirements present in different standards, three individual testing methods can be identified. Each of these will be analysed in detail in the ensuing chapters. There three different methods used for a transmitted overvoltage testing are:

- Transmitted overvoltage (TOV) test with the application of a low-voltage primary waveform (henceforth LV method) [10], [13], [15]
- Transmitted overvoltage (TOV) test with the application of a high-voltage primary waveform (henceforth HV method) [14]
- Ground shield check [11], [12]

2.1 Comparison of requirements for LV and HV method for testing transmitted overvoltages

Both LV and HV tests methods measure essentially the same parameter. The main difference between the two is how the impulse is generated, and what are the characteristics of the impulse. The referent primary voltage for evaluation of transmitted overvoltage for both cases is given in equation **(1)**. The value of the referent voltage assumes a disconnector operation at the maximal voltage for equipment and adds a peak factor of 1,6, which is in line with conclusions given in literature [2]. It should be noted that in literature [3] and [16] recorded peaks of overvoltages generated by disconnector operations reached values up to 2,4 per unit, depending on the capacitances on the source and load sides.

$$U_{pref} = 1{,}6 \times \frac{\sqrt{2}}{\sqrt{3}} \times U_m \quad \textbf{(1)}$$

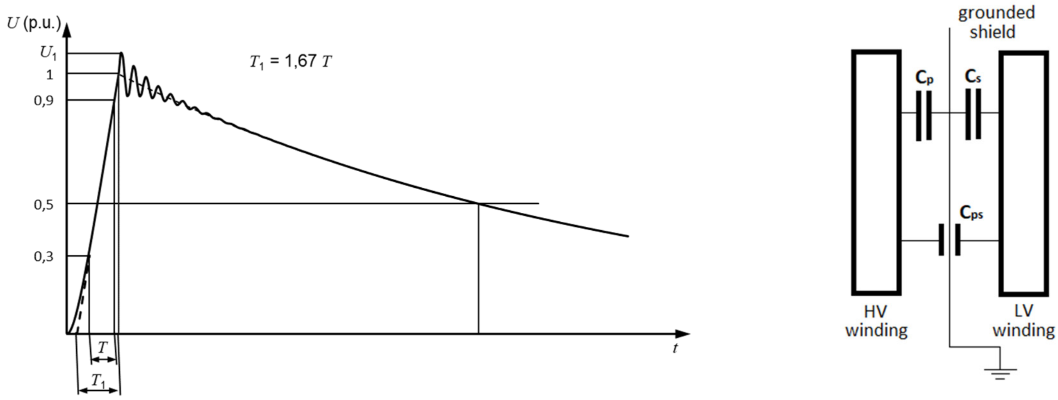
In actual testing an impulse waveform with a peak value of U_1 is applied to the primary terminal, while the voltage that appears across the secondary terminals (U_2) is measured. Depending on the method used the magnitude of these values will vary, as it will be discussed in the remainder of this chapter. The actual value of transmitted overvoltage (U_{tov}) is obtained using equation **(2)**, with the maximal allowable value set to 1,6 kV.

$$U_{tov} = U_{pref} \times \frac{U_2}{U_1} \quad \textbf{(2)}$$

This limit has been implemented in 1999 within a compilation of comments for drafts 38/231/CC (for current transformers) and 38/232/CC (for voltage transformers) [17]. The original value was 2 kV, which is in line with requirements for installation class 4, as given in the IEC 61000-4-5 standard for surge immunity test. However, the original value was reduced to 1,6 kV after consideration about the impedance mismatching between coaxial cable and actual burden [18]. It can be said that the requirement is a consequence of the fact that the devices connected to secondary terminals of instrument transformers are fairly standardized from an electromagnetic compatibility point of view, which is why this requirement makes sense.

The actual waveform to be applied depends on the method used, with the basic waveshape given in **Figure 1(a)**. The requirements given in different standard variants are given in **Table I**.

The originally proposed rise time of 0,5 µs ± 20%, which more accurately represents the high frequency overvoltages during disconnector operations, is easily achievable for a low voltage arbitrary waveform generator, while it is more difficult to achieve when a high voltage impulse is required, which mandates the use of an impulse generator. This can cause an excessive overshoot as reported in [8] and questionable repeatability of measured results, as discussed in [19]. That value was originally proposed in the earlier draft of the upcoming revised IEC 61869-1 standard (i.e. 38/631/CD). However, after a lengthy debate the requirement was set at the value given in **Table I**, which is also in line with recommendations given in [8].



(a) **(b)**

Figure 1 **(a) Basic waveshape for transmitted overvoltage testing (b) Schematical representation of ground shield check**

Table I **Comparison of waveshape characteristics required for tesing according to different standards**

	IEC 61869-1:2007	IEC 61869-1 38/652/CD	IEC/IEEE 63253-5713-8
Voltage level of primary impulse	LV impulse (typically between 100 – 500 V)	HV impulse $50 - 1{,}6 \times \frac{\sqrt{2}}{\sqrt{3}} \times U_m\ kV$	LV impulse $U_p \geq 5V$
T_1 (rise time)	0,5μs ± 20%	0,84 – 1,3 μs	0,5μs ± 20%
T_2 (time to half value)	≥ 50μs	≥ 50μs	≥ 50μs

Another point that has to be mentioned at this point is that the existing standard mandates using a mean curve for the primary voltage if oscillations at the crest are present [10]. On the other hand, the current draft specifies using the maximum amplitude of all oscillations of the primary wave [14]. The difference between the two also can influence actual testing, as it will be shown in later chapters of this paper.

The main motivation for switching from low voltage to high voltage method was the fact that it can both over and underestimate the actual level of transmitted overvoltage, and the lack of explicit guidance in how to guarantee the accuracy of generated wave, which can result in a large measurement uncertainty [8], [19]. The details on used measurement circuits and their differences will be described in chapter 3.

It should also be noted that the transmitted overvoltage test according to requirements given in **Table I** is specified as a special test, basically meaning that it is seldom performed and typically upon a customer request. There were initiatives to include the test as a type test (during the 38/631/CD stage), but given that the geometry and characteristics of instrument transformers can vary even within the same type (e.g. number of cores / windings, turn number, etc…) this approach made little sense. This is especially true for the high voltage method which does require a fair amount of setup and calibration time, which makes it less applicable for frequent testing.

2.2 Requirements for the ground shield check

Standards [11], [12] and [13] take a different approach in specifying the grounding shield test. The main difference is that the test does not verify the actual magnitude of transmitted overvoltage, but rather it verifies the existence of a grounded shield between the primary and secondary windings which drastically reduces the level of transmitted overvoltages. The existence of the grounded shield is verified by measurement of the following capacitances:

- Capacitance between primary and grounded shield (C_p)
- Capacitance between secondary and grounded shield (C_s)
- Capacitance between primary and secondary winding (C_{ps})

This measurement is schematically represented in **Figure 1(b)**. The existence of the grounded shield is verified if expression **(3)** is satisfied with a tolerance of ±10%. This also means that the transformer has successfully completed the test.

$$^1/_{C_{ps}} = {}^1/_{C_p} + {}^1/_{C_s} \tag{3}$$

Since this test is very simple to execute, it can easily be implemented as a routine test [12], [13], which is one of the main benefits of this approach. It is fast, simple and gives a good enough information for every bulk-produced item.

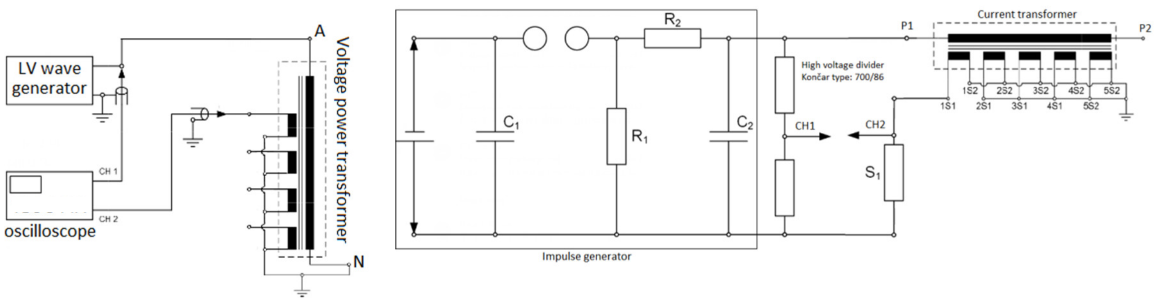
3. TEST CIRCUITS AND TESTED UNITS

Contributions of this paper are based on measurements performed on three distinct units; a 123 kV current transformer type AGU-123 with 5 cores (1 metering and 4 protection), a 123 kV voltage transformer type VPU-123 with three secondary windings (2 metering and 1 protection), and a 145 kV 50 kVA station service transformer type VPT-145 with a 120-240 V serial-parallel reconnectable power winding and two metering windings. All three units are shown in **Figure 2**.

(a) **(b)** **(c)**

Figure 2 **Transformers considered in this paper. (a) CT Type AGU-123 (b) VT Type VPU-123 (c) SSVT Type VPT-145 50 kVA**

As mentioned in the previous chapter, the main differences between HV and LV test methods are present in the parameters of waveforms applied which consequently require the use of different elements in test circuits. **Figure 3** shows schematic representations of LV and HV test setups for measurements used for the scope of this paper.



(a) **(b)**

Figure 3 **Testing circuit diagrams. (a) LV Method (b) HV Method**

For the LV test method, diagram shown in **Figure 3(a)** was used. Haefely recurrent surge generator, type: 481 was used to generate the primary voltage waveform, while a Tektronix oscilloscope, type DPO4054 was used to record the transmitted overvoltage waveform. The measurement system complies with the requirements of IEC 61083-1, as requested by the standard [14].

For the HV test method, diagram shown in **Figure 3(b)** was used. For the generation of primary voltage, a Haefely 2400 kV, 120 kWs impulse voltage generator was used. Since the peak values of primary voltage exceed 50 kV it is impossible to measure it with direct connection of oscilloscope as it is common practice in LV method. Instead, high-voltage resistive divider Končar type 700/86 was connected to the primary side of transformer and oscilloscope Tektronix type DPO4054 is connected to resistance R_2 of the divider meaning that all recorded values are multiplied with the transformation ratio of the divider.

Transmitted overvoltage (secondary signal) was measured by the same oscilloscope Tektronix type DPO4054 through a coaxial cable (type RG-58C/U) with wave impedance of 50 ohms terminated with a 50 ohm resistor, as it is requested by the standard [14]. Length of the coaxial cable was approximately 10 meters. The length was determined by the distance of the control room to the test object, as it was highly impractical to conduct measurements safely with a shorter cable. It should be noted that a lot of attention was paid to shielding and grounding the LV winding, coincident with experiences presented in [8].

4. TEST RESULT ANALYSIS

There are several analyses that are included in this chapter. Firstly, the focus is on evaluating the influence of rise time and peak oscillations on the transmitted overvoltage. This is crucial when implementing the HV method for testing. Secondly the focus is on comparing the LV and HV methods applied to the considered transformers. Lastly the focus is on comparing results for transferred overvoltage with and without the grounded screen present.

4.1 HV test results as a function of a rise time

Low voltage TOV test procedure uses waveshape with a front time of 0,5 µs. Since this waveshape is not easily generated by high-voltage impulse generators, current draft (38/652/CD) proposes allowed front times of applied voltage wave to be in range of 0,84 µs to 1,3 µs. To verify the impact of front time on the peak value of transmitted overvoltage, measurements with different front times on all three types of transformers were performed. Naturally, this necessitated the application of the HV test method. The actual rise times used were 0,5 µs, 0,84 µs and 1,2 µs. The first was used for comparison to the LV method, the second as the lowest value of the standard-required range and the third as the most common value, typically used for lightning impulse tests. Typical waveshapes of applied primary voltage waves and transmitted overvoltages are shown in **Figure 4** for core No. 1 of CT Type AGU-123.

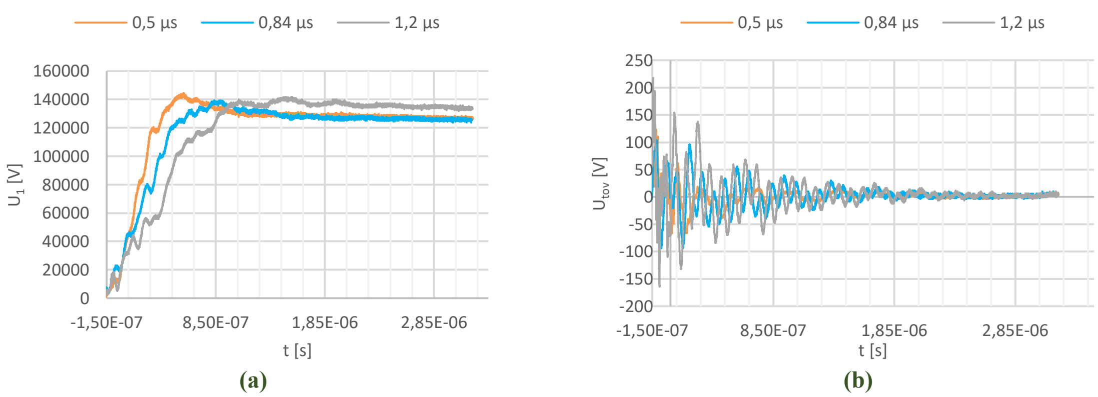
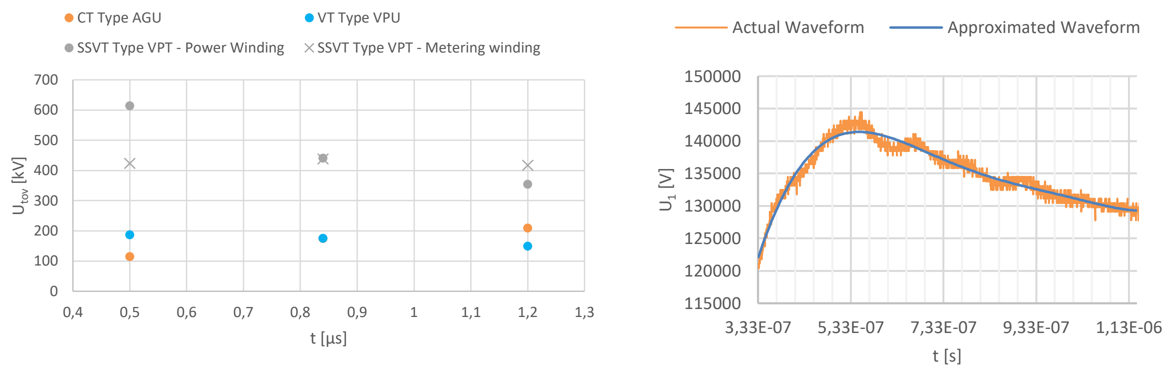


Figure 4 **Waveshape oscillograms for Core No. 1 of CT Type AGU-123 (a) Primary signal (b) Secondary signal**

It can be seen in **Figure 4(b)** that the peak value of the transmitted overvoltage will depend on the rise time of the applied primary waveform. This is represented in more detail in **Figure 5(a)**, which shows the effect of rise-time on U_{tov} for different types of transformers. Values shown in **Figure 5(a)** are plotted only for one core / winding for each type of a transformer since all other windings act similarly.



(a) **(b)**

Figure 5 **(a) Transmitted overvoltage as a function of rise-time for different transformers (b) Comparsion of actual and approximated primary voltage waveforms**

Values of transmitted overvoltages for current transformer type AGU-123 increase as rise-time increases while for voltage transformer type VPU-123 and measuring windings of SSVT type VPT-145 values of transmitted overvoltages slightly decrease as rise-time increases. The difference in behaviour is most probably attributed to different geometry between the transformer types and should be investigated further. It should be noted that the setup and parameters of the actual impulse generator used are also reported to have a significant influence [8], [20]. What is clear from these results is the fact that using different rise time the test can be performed in a way that it garners a better performance in terms of transmitted overvoltage. For that reason, and the sake of consistency, the recommendation of the authors is to use a constant rise time for each transformer type, the one which was empirically found to give the worst TOV performance.

The inconsistency between different rise times also lead to the investigation whether the oscillations in primary waveform play a role in TOV performance. For that reason, a comparison was made between results obtained with using the mean curve, approximated with a polynomial of the 6th order and actual measured curve. The comparison of the two curves is shown in **Figure 5(b)**, whereas actual results are shown in **Table III**. As it can be seen from the table, the difference is lower than 20%, which compared to the discrepancies between different rise times is very low, especially for rise times of 0,84 and 1,2 µs, so that influence can be excluded.

Table II **Percentage error between Utov using acutual and approximated primary waveforms**

Transformer type	Percentage error between U_{tov} using acutual and approximated primary waveforms *Δ [%]*		
	Rise time 0,5µs	Rise time 0,84 µs	Rise time 1,2 µs
CT Type AGU-123	3,4	1,9	6,8
VT Type VPU-123	5,8	5,1	2,8
SSVT Type VPT-145 – Power Winding	21,7	9,1	3,5
SSVT Type VPT-145 – Metering winding	12,5	10,6	3,5

4.2 Comparison of LV and HV test results

The next analysis performed was the comparison of LV and HV methods, as described in chapters 2 and 3. The comparison of primary and secondary signals for core No. 1 of CT Type AGU-123 is given in **Figure 6**. The values of primary voltage are expressed in per unit values to be comparable. The complete comparison of results is given in **Table III** - **Table V**.

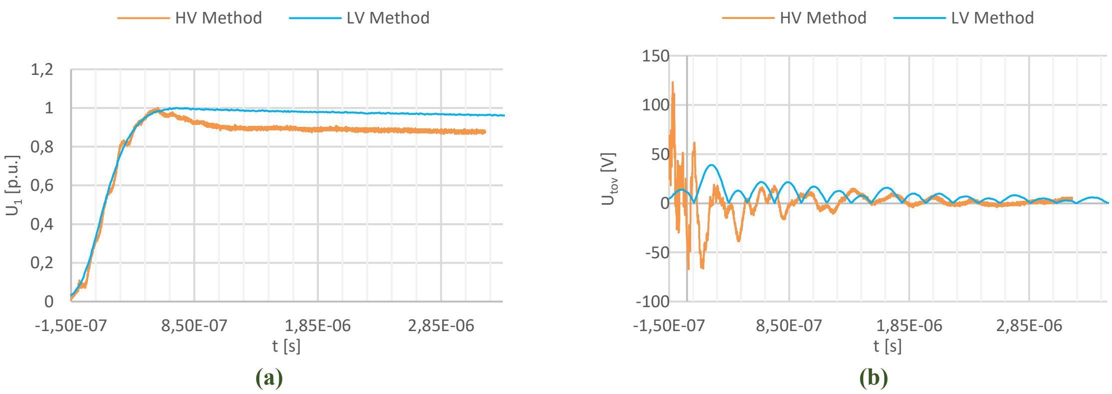


Figure 6 **Comparison of HV and LV methods for core No. 1 of CT Type AGU-123 (a) Primary signal (b) Secondary signal**

Table III **Comparison of LV and HV measurements for CT Type AGU-123**

Test Method	U_{tov} [V]				
	Core No. 1	Core No. 2	Core No. 3	Core No. 4	Core No. 5
LV Method	38,8	61,6	62,2	65,7	129,2
HV Method	137,0	114,5	139,2	132,5	140,8

Table IV **Comparison of LV and HV measurements for VT Type VPU-123**

Test Method	U_{tov} [V]		
	Secondary winding No.1	Secondary winding No.2	Secondary winding No.3
LV Method	169,0	168,8	172,8
HV Method	186,2	187,4	220,9

Table V **Comparison of LV and HV measurements for SSVT Type VPT-145**

Test Method	U_{tov} [V]			
	Power winding parallel connection	Power winding serial connection	Metering winding No.1	Metering winding No.2
LV Method	2336,7	1645,7	1257,8	1141,9
HV Method	666,4	613,9	422,9	442,0

Looking at the result comparison for all three types of transformers considered, it is clear that the LV method can both overestimate and underestimate results gained by the HV method, depending on the transformer tested. A similar discrepancy of results between the HV and LV methods was found and addressed in [8]. The conclusions of that paper also apply to the results displayed within this paper.

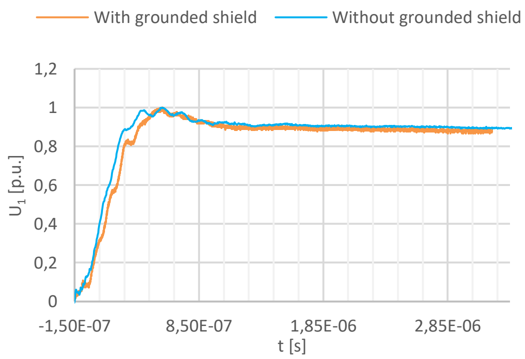
Furthermore, the differences in TOV performance between different cores (windings) are also more pronounced with the LV method and less logical. Due to the length constraints of this paper it is not possible to thoroughly analyse the differences in internal geometries of the tested transformers, however it can be concluded that the HV method gives logical values of U_{tov} taking into account the internal geometry and differences between individual windings. Another influencing factor could be the magnitude of applied voltage for the LV method, which was analysed in [19] and was found not to be an influence.

With all this in mind it is justified to question the applicability of the LV method on voltage levels present during actual operation, and the authors' recommendation is to use the HV method as relevant.

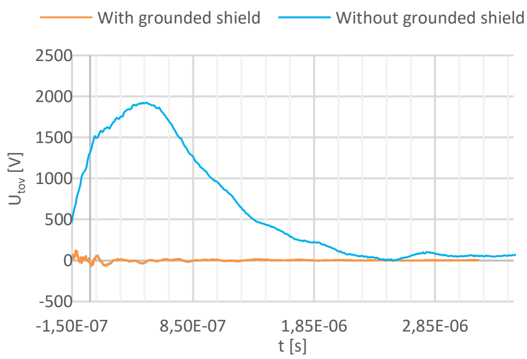
4.3 Influence of grounded shield

The final analysis performed was the evaluation of the grounded shield and the influence it has on the transmitted overvoltages. All units considered within this paper had grounded shields included and passed the grounding shield check per equation **(3)** successfully. For this analysis, the tests were performed both with the grounded shield grounded as in service and with the grounded shield ungrounded. It should be noted that the primary voltage had to be limited to 10 kV in order not to compromise the insulation of the transformer. The comparison of primary and secondary signals for core No. 1 of CT Type AGU-123 is given in **Figure 6**. The results for all transformers considered are given in **Table VI**. Results for different types of transformers are shown for one core / winding only, since all others exhibit very similar results.

It is obvious that the omission of a grounded shield has a very unfavourable impact on transmitted overvoltages (U_{tov} values are drastically higher). These results confirm that the inclusion of a grounded shield is necessary to limit the transmitted overvoltages. In that sense, performing a grounded shield test is extremely useful, even though the test does not give an explicit information about the magnitude of transmitted overvoltages. It is a simple test that is easily implemented in routine test procedures, and as such is highly recommended by the authors.



(a)



(b)

Figure 7 **Influence of the grounded shield between primary and secondary windings (a) Primary signal (b) Secondary signal**

Table VI **Comparison U_{tov} for different transformers with different configurations of the grounded screen**

Grounded screen	U_{tov} [V]			
	CT Type AGU-123	VT Type VPU-123	SSVT Type VPT-145 – Power Winding	SSVT Type VPT-145 – Metering winding
Included	38,8	169,0	599,3	350,2
Not included	1922,9	2928,0	3244,1	2596,2

5 SPECIAL CONSIDERATIONS FOR STATION SERVICE VOLTAGE TRANSFORMERS

While Station Service Voltage Transformers share their general construction principle with inductive voltage transformers, there are several factors that can differentiate them from conventional instrument transformers. The first differentiating factor is the transformation ratio that can be 2 – 20 times lower than inductive voltage transformers of the same voltage class, as specified in [15]. Moreover, these units often contain windings intended for individual, serial, and parallel connection. The second differentiating factor is that load connected to their secondary windings can vary drastically, depending on the application (e.g. auxiliary supply, rural electrification, supply of power to industrial consumers, etc.) [9]. The secondary circuits then should be subject to insulation coordination that is more expansive than for meters and protection relays that have more standardized characteristics. The third differentiating factor is that station service voltage transformers can contain metering/protection windings intended for connection of metering or protective devices in addition to windings intended for power supply. These windings can have different performance in terms of transmitted overvoltages, as it will be discussed in this chapter. As indicated in chapter 3, the considered unit has both types of windings included.

For these reasons it is questionable whether station service voltage transformers can fully conform to requirements for instrument transformers and more importantly should they.

The aggregated testing results for SSVT Type VPT-145 are presented in **Table VII**. It is apparent that there is a difference between the performance of metering windings and power winding, which is logical since they have different geometric displacement and turn number. Typically, it is exhibited that the power winding exhibits a larger U_{tov}, which is indirectly attributed to a lower transformation ratio. Even though it is reported in [21] that the value of transmitted overvoltages bears no relationship to the turns ratio of the transformer, that statement is not entirely true, because for SSVTs (and other types of instrument transformers) the turn number is directly connected to the low voltage winding capacitance which directly influences the transmitted overvoltages [19]. For that reason it is expected that SSVTs will have a larger U_{tov} than other instrument transformer types, as corroborated by **Table IV**, **Table V** and **Table VII**.

Table VII **TOV test results for 145 kV Station Service Voltage Transformer**

Test Method	Rise time[µs]	U_1[kV]	U_{tov} [V]			
			Power winding parallel connection	Power winding serial connection	Metering winding No.1	Metering winding No.2
LV test results	0,5	0,2	2336,7	1145,7	1267,8	1141,9
		0,3	2496,5	1599,6	1418,4	1280,9
	0,84	0,2	1143,7	952,0	1088,7	1041,3
		0,3	1207,8	915,4	1109,6	1080,8
	1,2	0,2	490,4	361,0	197,5	179,6
		0,3	522,8	381,3	217,7	197,5
HV test results	0,5	50	666,4	613,9	422,9	442,0
	0,84	50	495,2	440,8	437,9	381,0
	1,2	50	425,9	354,2	416,8	387,5

When taking into account the above considerations coupled with the fact that according to [15], the secondary voltage of SSVTs power winding can be as high as 1000 V and that SSVTs are used for a multitude of applications, as disclosed in [9], implementing the criteria required by [14], as described in Chapter 2, does not make sense. Instead, a better alternative is to look towards the insulation coordination standards [22] and [23]. It is the authors' recommendation to use the overvoltage category II unless a specific application is at hand. The proposed requirements, as defined in table 44.B of reference [22] are given in **Table VIII**.

Table VIII **Proposed overvoltage requirements, as defined in [22]**

Nominal voltage of the installation		Required impulse withstand voltage [kV]			
Three-phase systems	Single-phase systems with middle point	Category IV – Equipment at the origin of installation	Category III – Equipment of distribution and final circuits	Category II – Appliances and current-using equipment	Category I – Specially protected equipment
-	120-240	4	2,5	1,6	0,8
230/400 277/480	-	6	4	2,5	1,5
400/690	-	8	6	4	2,5
1000	-	12	8	6	4
Recommendation		Not recommended	For specific applications	Recommended as default	For specific applications

Observing the results for metering windings, presented in **Table VII**, it is clear that values of transmitted overvoltages are smaller than for power windings, which is expected. Also, it should be noted that measuring and protection windings supply the same equipment as do instrument transformers so standard requirements for them should be in accordance with valid standard for instrument transformers.

As mentioned in Chapter 4.2 the LV method can highly overestimate transferred overvoltages. Coincidentally, the obtained U_{tov} values in parallel connection are significantly higher than in serial connection, which is not expected since the capacitance between windings stays the same. Another problem with the application of LV method is huge dispersion of test results when varying rise-time of applied voltage impulse (difference up to five times between 0,5 and 1,2 µs), so it is questionable whether LV method is acceptable for testing transferred overvoltages on station service voltage transformers. Since it is not specified whether serial or parallel connection has larger values of transmitted overvoltages tests should be performed for all available connections.

6 CONCLUSION

This paper provides a detailed overview of different aspects of transmitted overvoltage testing on instrument transformers intended for Air Insulated Substation installations. Different approaches were analysed on different types of instrument transformers. There are several conclusions that can be drawn on the foundation of all analyses performed.

The use of LV method proved to be fairly inconsistent, and it was confirmed again that it can grossly underestimate, or overestimate the transmitted overvoltage performance, depending on the type of transformer being tested. For that reason, the application of HV method is recommended, as specified in [14].

The HV method can also be very sensitive to the test setup, earthing, transformer ratings and other parameters, especially if lower rise times are applied. A range of 0,84 -1,3 µs, as defined [14] is sensible. It is recommended that a constant rise time is used for a specific transformer type, otherwise the results can be manipulated to achieve a better performance during testing. A typical 1,2 / 50 µs waveform is highly recommended to achieve the best result repeatability and consistency. Furthermore, it was proven that it is not necessary to use a mean curve for the primary voltage, rather an measured peak value is sufficient.

It is clear that the inclusion of a grounded shield drastically reduces the transmitted overvoltages, and for that reason the grounded shield check should be a recommended routine test in all international standards. The dedicated transmitted overvoltage test should remain a special test. The best practice in this regard is given in [13], as both approaches are integrated in the same standard. It would be ideal if other international standards would follow the same approach.

Station service voltage transformers should not be exempt from transmitted overvoltage requirements as they operate under the same conditions as instrument transformers. Due to a larger range of available secondary voltages and a multitude of applications the transmitted overvoltage requirements should be defined as suggested in chapter 5 and should be linked to the rated secondary voltage. The metering windings of SSVTs should conform to the same requirements as conventional instrument transformers. It is recommended to use HV testing when verifying the transmitted overvoltage performance of SSVTs. If specific categories of transmitted overvoltages are required, additional shielding or external overvoltage limiting devices should be used.

As a final note, the requirements for transmitted overvoltages are a constantly evolving topic that is connected to the evolution of the entire power system. For that reason, this paper is a valuable resource for fundamental understanding of transmitted overvoltage requirements, testing scenarios, practical constraints and best practices. This makes it an excellent basis for future research and evolution of requirements present in different standards.

BIBLIOGRAPHY

[1] Z. Bajramović, I. Turković, A. Mujezinović, A. Carsimamovic, A. Muhamerović. “Overvoltages in Secondary Circuits of Air-Insulated Substation Due to Disconnector Switching”, 2012 IEEE International Conference on Power System Technology (POWERCON), Auckland, NZ, 2012.

[2] S. Carsimamovic, Z. Bajramović, M. Veledar, M. Ljevak, A. Carsimamovic, P. Osmokrović. “Influence of Resistance of Electric Arc on Transients Due to Disconnector Switching in Air-Insulated Substations”, IEEE Transactions on Plasma Science, Vol. 36, No. 5, October 2008, pages 2560-2565

[3] Y. Chai, P. A. A. F. Wouters, R. T. W. J. van Hoppe, R. P. P. Smeets, D.F. Peelo, “Capacitive Current Interruption with Air-Break High Voltage Disconnectors”, IEEE Transactions on Power Delivery, Vol. 25, No. 2, April 2010, Pages 762-769

[4] T. Župan, I. Novko, I. Žiger, “Capacitively Graded Oil-Paper Insulation Behavior Under Repeated Flashover Conditions” IEEE Electrical Insulation Conference, 2021

[5] B. Filipović-Grčić, I. Uglešić, V. Milardić, D. Filipović-Grčić, “Analysis of electromagnetic transients in secondary circuits due to disconnector switching in 400kV air-insulated substation”, Electric Power System Research, Vol 115. 2014, pages 11-17.

[6] S. Adhikari, C. Pallem, D. Mueller, T. Grebe, B. Zavadil and K. Little, "Multiple prestriking phenomenon in high voltage transmission substations: Modeling and simulation," 2016 IEEE Power and Energy Society General Meeting (PESGM), Boston, MA, 2016, pages. 1-5.

[7] Z. Bajramović, I. Turković, A. Mujezinović, A. Carsimamovic, A. Muhamerović. “Measures to Reduce Electromagnetic Influences on Substation Secondary Circuits”, International Symposium on Electronics in Marine (ELMAR), Croatia, 2012

[8] A. P. Elg, F. Garnacho, T. Garcia, J. Rovira, J. Hallstrom, T. Nieminen, “Traceable Measurement of Transmitted Overvoltages in Instrument Transformers”, Cigre Science and Engineering, (16), 2019 pages 58-63

[9] I. Žiger, B. Bojanić, D. Krajtner, “Open-core Power Voltage Transformer: Concept, Properties, Application”, IEEE Energycon, Dubrovnik, Croatia, 2014.

[10] IEC 61869-1:2007, “Instrument Transformers - Part 1: General Requirements”, 2007

[11] IEEE Standard Requirements for Instrument Transformers, IEEE Standard C57.13-2016, 2016.

[12] IEEE Standard for Performance and Test Requirements for Instrument Transformers of Nominal System Voltage of 115 kV and above, IEEE Standard C57.13.5-2019”, 2020.

[13] CAN/CSA-C61896-1:14, “Instrument Transformers - Part 1: General Requirements”, 2014

[14] 38/652/CD IEC 61869-1 ED2, “Instrument Transformers - Part 1: General Requirements” Committee Draft, 2021

[15] 38/660/CD IEC/IEEE 63256-5713-8 ED1 “Station Service Voltage Transformers”, Committee Draft, 2021

[16] D.F. Peelo, J.H. Sawada, R.R. Sunga, R.P.P. Smeets, J.G. Krone Hapabam B.V., L. Van der Sluis, “Current Interruption With High Voltage Air-Break Disconnectors”, CIGRE Paris Session, 2004.

[17] M. Poljak, “Transient Overvoltages in the Instrument Transformers Secondary Circuits”, 4th HRO Cigre Session, Cavtat, Croatia, 1999

[18] IEC 61000-4-5 ED3.0, “Electromagnetic compatibility (EMC) – Part 4-5: Testing and measurement techniques – Surge immunity test, 2014

[19] T. Perković, “Transmitted Overvoltages in high-voltage instrument transformers”, Master Thesis, Faculty of Electrical Engineering and Computing, Zagreb, Croatia, 2021.

[20] A. P. Elg, “Qualifying a transient recorder for traceable measurements of very fast transients”, Conference on Precision Electromagentic Measurements, CPEM, Paris, France, 2018.

[21] A. Greenwood, “Electrical Transients in Power Systems”, John Wiley & Sons, Inc. 2nd edition, 1991.

[22] IEC 60364-4-44:2009, “Low-voltage electrical installations - Part 4-44: Protection for safety - Protection against voltage disturbances and electromagnetic disturbances”, 2009.

[23] IEC 60664-1:2020, “Insulation coordination for equipment within low-voltage supply systems - Part 1: Principles, requirements and tests”, 2020.